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Quantitative Capability Delivery Increments: a novel approach for estimating and assessing DoD future network needs

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While Joint network enabled operations promise the DoD benefits in terms of improved force agility and effectiveness, these also pose significant challenges for decision makers faced with the job of identifying major gaps and the potential contribution of investment alternatives. Traditional analysis methods based on information exchange requirements have been found to be resource intensive, time consuming, and often limited by the experience of the supporting subject matter experts who are unable to anticipate either the situations that might arise or the manner in which new capabilities and business processes might evolve over time. This paper proposes a new but complementary approach for estimating future demand for network capability based on the premise that aggregate demand for network capability is driven by trends in communication devices used to access the network. The paper describes the Quantitative Capabilities Delivery Increments (QCDI) demand model developed to meet DoD's need to project future network demands of military units.

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INTRODUCTION

With over 2.1 million active military and civilian personnel and a budget in excess of $600 billion a year, the U.S. military is one on the largest and most complex organizations in the world by virtually any measure.[1] The legal and policy constraints governing the equipping of this force necessitate specifying the parameters of future systems years ahead of planned delivery. Increasing mandates to view capability needs from a joint and in some cases enterprise perspective (in addition to service-specific imperatives)[2] only add to the complexity and difficulty of determining the network needs of the future force.[3]

With threats that vary from global terrorist movements, insurgencies in failed states, and major nation states, a key element of the DoD strategy[4] for addressing the new environment is to transform to a net enabled agile force that can span the full spectrum of crisis and conflict, ranging from natural disasters through irregular warfare to major conventional operations. It is recognized at the highest levels in DoD that to be successful in this endeavor commanders and warfighters must be provided with a Joint network that provides a decisive advantage over adversaries. This network must be resilient to attack and robust in performance across the full range of situations that might be encountered—from traditional roles such as support of convoy operations as shown in figure 1, to secure connection of the newest unmanned sensor platform with tactical edge ground forces.

Determining the specific levels of performance required for this type of network poses great challenges for decision makers at all levels and, in particular, for the analysts that advise them. They grapple with questions such as: how much capability is enough to assure mission success? How might degraded network performance impact the force's ability to employ preferred methods, accomplish essential tasks, and achieve desired end states? Or, ultimately, how can investment alternatives be weighed in the context of mitigation of mission risks? Because of the critical role of the Joint network, it is important to understand the impact of network capability on mission success when making key decisions related to investment, system design and development, and the operational plans that these systems support.

Figure 1. Human integration of convoy operations using Joint network components[5]

Many commercial endeavors owe their success in large part to the ability to obtain a clear understanding[6] of how information technology and networks can enable innovative business processes that provide a quantifiable competitive advantage in the global market place. There are a host of network based innovations intended to attract and keep customers.[7] When evolving such enterprises, companies attempt to understand not only the role of their networks in gaining competitive advantage, but also how the size and performance of their network contribute to their bottom line, their ultimate measure of mission success.[8]

The DoD, which admittedly differs from commercial industry in some important ways, has struggled with mixed success for years to relate information systems to mission outcome. Decision-makers have often been forced to resort to ad hoc prioritization of requirements that bubble up from below with little quantitative understanding of how the related programs contribute to mission success. The growing importance of a capable global Joint network in enabling force agility and cyber operations has increased the need to better understand and ultimately quantify the role of the network in meeting mission needs. A first step in better understanding the role of future networks is achieving consistent and repeatable estimates of future demand across DoD. The Quantitative Capability Delivery Increments model provides an analytic framework and tool set to meet this need.

The Nature of the Analytic Problem

The first big challenge in modeling future network demand for DoD is "The Curse of Dimensionality". When viewed on a DoD wide basis, there is a broad range of situations, operations, missions, tasks and functions to consider. Military forces from the four Services often have different information support needs, as do the C2, Intelligence and logistics communities that support them. The Joint network is comprised of several functional domains and a large number of information system programs. Finally, both the users and providers reflect a multiplicity of cultures, terminology and perspectives, and all these must be considered when seeking enterprise-wide solutions.

The second major problem is the difficulty of forecasting demand for network capability in order to support today's procurement of tomorrow's systems. Due to the dynamic and uncertain nature of operational environments shaped by human behavior, information exchange needs are continually changing. Adversaries adopt new Tactics, Techniques & Procedures (TTPs) -- equivalent to business processes in commercial industry, to counter successful strategies. Warfighters must respond to the resulting surprises by adapting their own TTPs. Technology and business processes co-evolve in unpredictable ways; users discover innovative ways of using new information system capabilities, and these new methods give rise to requirements for additional information system capabilities. In the large analysts are faced with broad, multidimensional, heterogeneous, complex systems operating in a highly uncertain environment.

An array of techniques and associated tools can be used to address selected aspects of this problem. The most commonly used methods rely on stating requirements for exchange of information among users or their supporting information systems; i.e. Information Exchange Requirements (IERs). Another approach is to canvas Subject Matter Experts (SMEs) with particular but often narrow areas of expertise in network systems or operations to identify key network attributes and needed quantitative values for these attributes. When estimating the demand for aggregate network capabilities, metrics for various domains are often inconsistent and values for the same domains can vary widely due to heavy reliance on inputs from SMEs who are limited by their specific operational experiences. Steps necessary to aggregate IERs quickly explode as the number of users, operations, and domains increase. Since both these methods are designed for specific systems or operations, these have significant limitations in support of diverse scenarios and to the enterprise as a whole.

Creating a New Analytical Support Environment

To address the overarching analytical challenge described above, a common framework with consistent metrics, a quantifiable repeatable methodology, and supporting tools that allow tailoring to a wide range of needs in a timely and responsive manner are needed. The necessary change in capability is summarized in fig. 1. In order to overcome the formidable impediments described earlier and achieve this vision, a new approach is required.

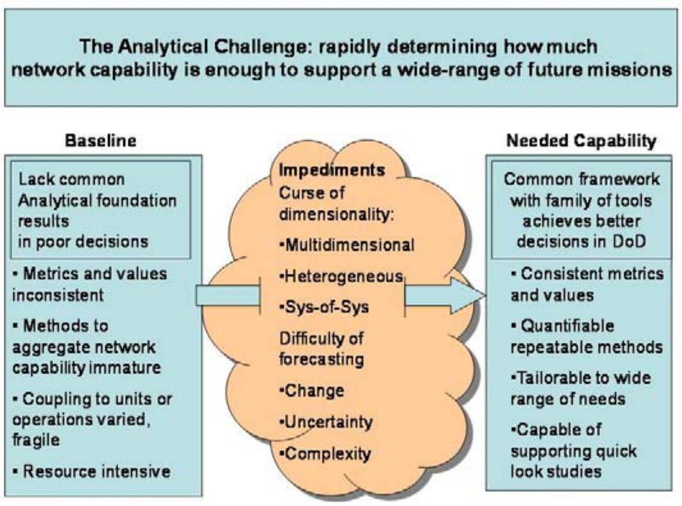

Figure 2. Changes needed to meet the analytic challenge of estimating future network needs

To deal with the dimensionality challenge inherent in an enterprise-wide framework and exacerbated by historical IER and SME based approaches, we propose a solution that models aggregate capability at a low but consistent level of resolution. The design goal of the model is timely support to investment and resource allocation decisions of interest in DoD and the Services today. The approach is to use a relatively small set of key dimensions and driving variables to model future network demand. This approach trades precision for tractability, but permits the rapid generation of aggregate estimates and the identification of major shortfalls. As necessary, more detailed analyses can then be focused in the most important areas. The key is an approach that allows choice of dimensions and variables that are the major drivers in investment decision while explicitly examining and discarding factors whose impact on aggregated capability is small; e.g. less than one percent.

A BASIS FOR THE JOINT NETWORK

In addition to policy and other top-down driven mandates, the Services and individual commands at all echelons have increasingly recognized the need for interoperable networks and information systems at and across all levels. Where once hierarchal networks mirroring formal Command and Control channels were deemed sufficient, the need to reliably and rapidly exchange rich information horizontally across an interdependent joint force has become a commonly accepted requirement[9]—driven by not by policy, but by operational imperatives in Iraq and Afghanistan.

Although there are natural limits to the Joint network driven by security, technical feasibility, and culture (few would advocate that nuclear command and control networks be completely integrated with common user networks), these cases are increasingly viewed as the exception. This is especially true as the “born digital” generation of users enter the military, since they are culturally much more comfortable with exchanging information with individuals and groups outside of formal boundaries. Technology advancements and practical necessity have combined to find innovative ways to connect networks and devices well beyond the intent of the original designers. The net result of these trends is that virtually all data networks (even legacy) are or are being connected as part of the common DoD network, often referred to as the Global Information Grid. Figure 3 illustrates this trend.

Soldiers and others can now read the latest Army news on their iPhones, thanks to a new application created by the team that developed the Army's Web site, (Photo by U.S. Army)

Figure 3. Rapidly Growing Connections of Device and Network Types

Joint planning for future military capabilities falls under the legal authority of the Chairman of the Joint Chiefs of Staff. These responsibilities are executed in large part through the Joint Requirements Oversight Council[10] via the Joint Capabilities Integration and Development System (JCIDS).[11] JCIDS guidance specifies the use of joint concepts and Concept of Operation documents as the starting point for estimation of network support required for future military operations. Within the Net-Centric functional area, a series of JCIDs concept and related capability document, such as the Net-Centric Operations Environment Joint Integration Concept,[12] indicate the network needs of the joint force in the 2015-2025 timeframe. The collective evolution of demand over time described in these documents is captured in the Capability Delivery Increments (CDI) document, approved by the Joint Staff in June 2009.[13] Figure 4 shows the current Net-Centric capabilities taxonomy as reflected in the CDI and related documents.

Apart from resource priorities, many factors may hinder evolution of capabilities within the Net-Centric area. For instance, technology development often does not reach expected levels of maturity in time to field viable capabilities on schedule. New systems must fit into existing architectures often built around legacy systems.

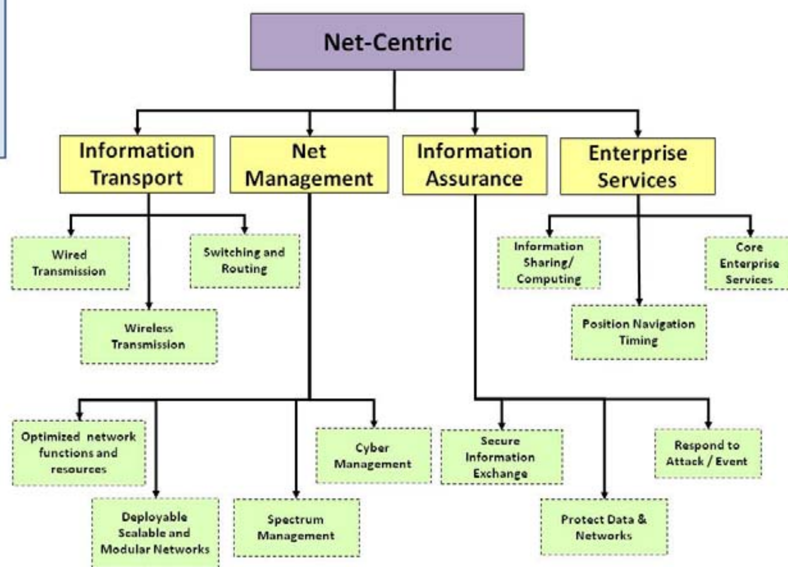

Figure 4. Net-Centric Joint Capability Areas Taxonomy for Tiers 1 to 3

The performance of new systems is often reduced by the need to meet architectural constraints. The DoD relies on complex platforms such as aircraft, tanks, and ships. The network capabilities associated with these platforms must be upgraded in synchronization with non-network capabilities and based on schedules determined years in advance. Special DoD procurement, policy, security, and other regulations often limit how quickly new technologies can be adopted. These and other factors present technical feasibility constraints to the evolution and adoption of network capabilities as envisioned in the CDI. The Quantitative Capability Delivery Increments (QCDI) model projects demand over time for Joint network capabilities by accounting for the demand called for in the family of capability documents as constrained by the above factors.

USER-LEVEL NETWORK DEMAND

In order to determine network capability needs from a joint perspective in a way that is applicable across the spectrum of joint operations and organizations (and thus meet the objectives of the QCDI model), it is necessary to start with some basic assertions about the nature of the Joint network. The first and possibly most critical of these is that users, regardless of Service, can be grouped into classes with similar network demands. This assertion allows for flexible representation of the network needs of users in a joint context independent of Service-specific considerations (doctrine, policy, etc.), using a limited number of user classes whose demands are based on factors such as the general role of the users in the Joint network, anticipated level of access to the Joint network, anticipated form factor of devices providing access to the Joint network, and other reasons that will be discussed later in this paper.

In addition to variation by user class, demand for Joint network capability may also be different at different echelons and domains. The QCDI uses a three-level echelon tiering – “core” users who connect to the network at permanent stations; “intermediate” users who connect from non-permanent, but generally fixed, stations; and “tactical” users who connect through an infrastructure that is brought with them to theater and is largely moveable and/or mobile. Likewise, the QCDI also allows for the fact that user demand may differ depending on whether users’ Joint network access is via terrestrial, aerial, or maritime networks. Figure 5 illustrates the user class structure employed in the QCDI demand model, with user classes present in the various user areas, which are defined by Tier and Domain.

	Core	Intermediate	Tactical Edge
Terrestrial/ Ground	Local Worker CP High CP Low Commander USS High USS Low UAS High UAS Low Static Sensor	Dismnted Ground Surface Mobile Local Worker CP High CP Low Commander USS High USS Low UAS High UAS Low Static Sensor	Dismnted Ground Surface Mobile Local Worker CP High CP Low Commander USS High USS Low UAS High UAS Low Static Sensor
Airborne		Commander C2 Air ISR Air UAS High	Commander LO Air Mobility Air TAC Air UAS High
Maritime		Surface Mobile Local Worker CP High CP Low Commander USS High USS Low UAS High UAS Low Static Sensor	Surface Mobile Local Worker CP High CP Low Commander USS High USS Low UAS Low Static Sensor

Figure 5. QCDI User Classes by domain (Ground, Airborne, Maritime) and Tier (Core, Intermediate, Edge)

Non human users are an increasingly important driver of demand for Joint network capabilities. As more functions become automated in DoD and commercial information systems, the number of non-human users of the network increases. These changes often reflect incremental changes in force structure but sometimes represent subtle additions to supporting systems, imperceptible to the everyday human users of the network.

One type of non-human user is found in unmanned systems. DoD has made plans to field a rapidly growing number and diversity of such systems ranging from the well-known Unmanned Aerial Systems such as the Predator, to a host of small ground based robots and sensors, intended to augment and replace humans in especially dangerous missions, the network demand of these systems going forward is especially important to account for. The growth in these systems has exceeded 100 percent per year and is likely to continue at high rates into the foreseeable future.[14] In the QCDI model, unmanned systems and sensors are represented as explicit user classes that generate their own demand for Joint network capabilities. That demand is associated with their anticipated capabilities and uses.

Another aspect of non-human demand derives from the use of smart software agents, or smart agents for short, that act on behalf of Joint network users. Such software may alert supported users to upcoming meetings or to recently received e-mail and telephone calls. In the case of DoD systems and platforms, some programs are already planning for advanced aircraft that will download the mission status of many subsystems to a host or to a remote server to automate the delivery of spare parts. In the QCDI model, agent demand is depicted as a multiplicative factor that augments (or mitigates in some cases) the demand of human users the agents are supporting.

User-level demand is expected to continue to grow over time as network technology and users' ability to exploit it co-evolve. For capacity-related metrics, the QCDI asserts that the historic trends of exponential growth in users' network demand will continue, with some variation among user classes/echelons/domains to reflect technical realities that may be particular to some situations. Typical growth estimates for these types of metrics follow extrapolations of current trends as shown in Figure 6. For quality-related metrics, the QCDI models growth in quality consistent with increased reliance on the Joint network for warfighting functions as described in the Net Centric Capability Delivery Increments (CDI) document and bounded by technology improvements allowing for better efficiency, availability, and reliability over time.

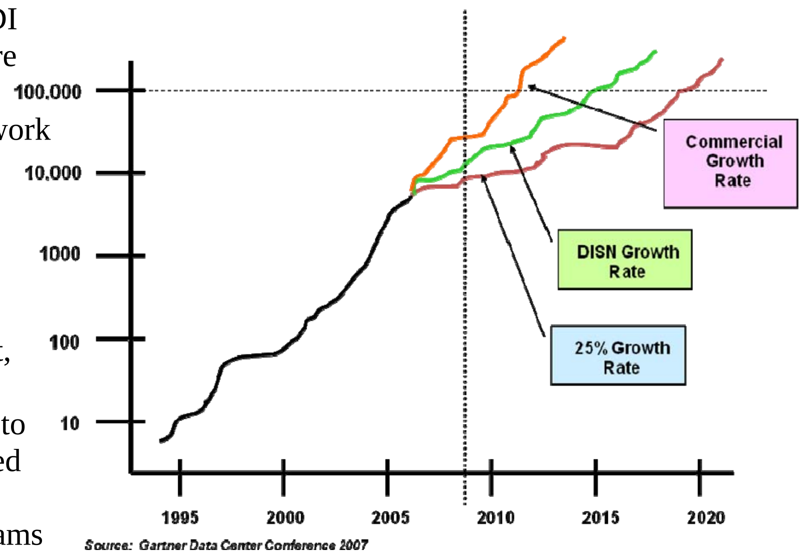

Figure 6. Typical commercial analyst extrapolation of continued network demand growth

The QCDI model also includes factors to account for infrastructure considerations such as overhead. While the demand of individual users is not influenced by overhead considerations, the additional demand generated by the activities and infrastructure associated with key network functions such as network management, information assurance, and the provision of enterprise services is real and must be accounted for in order to enable meaningful assessments of supply against demand. The

Joint network needs resulting from these kinds of activities and functions are captured in the demand as "infrastructure users".

In addition to reflecting the demand for different classes of users across different user areas and timeframes, the QCDI model also produces estimates for different types of demand. Characterization of the assumed mobility needs of different user classes allows for estimation of whether the demand of users in each class is on-the-move demand or at-the-halt demand, which is important in determining what kinds of systems and programs are able to satisfy that demand. Factors are also provided that estimate the proportion of the user's bandwidth demand that is local to the user's area or that is destined to or originates from another user area. Similarly, the QCDI provides estimates of the upload/ download demand ratio for users. The model also includes an explicit estimate of the demand for protected communications at the user level, to allow assessments of the adequacy of Joint network capacity in hostile and threatened environments.

QUANTITATIVE METRICS FRAMEWORK

To facilitate analysis and provide useful results, demand must be quantified. This requires well defined metrics and a method for estimating values for these metrics. The following characteristics were used to select the metrics chosen:

User oriented: While metric frameworks often view the network from the perspective of the Service Provider (e.g. how much backbone capacity is needed?) it is possible to adopt a user point of view (e.g. how much data does a user typically need to send or receive and how often?) This perspective allows full consideration of aspects of network capability that can be directly related to the operational needs of the user (the ultimate customer) who should not have to be concerned about how his demand is actually being met.

Widely Applicable: Metrics need to apply to a wide range of operational use cases and information technology programs. They must also permit measurement of supply and demand for key functional segments of the network; i.e. the Tier II JCA capabilities: Information Transport, Enterprise Services, Information Assurance and Network Management. They should also be applicable to all user classes and echelons. Indeed they need to be suitable to provide a consistent view of the entire joint force or major portions, as appropriate to the issue at hand.

Easy to apply: In order to facilitate decision making, particularly at the higher levels of governance, the number of metrics should be kept to a minimal set. Also, the data to support measurement of capability demanded or supplied must be readily obtainable in official documentation or other available sources.

Information Transport
- Typical Req. DR (Mbps)
- Protected Comm. DR (Mbps)
- Voice DR (Mbps)
- Availability (%)
- Voice Packet Delivery Ratio (%)
- Packet Delivery Ratio (%) (min)
- Comm. Set-up time (min) (max)
- Data End-to-End Delay (sec) (max)
- Voice End-to-End Delay (sec) (max)
- Upload (%)
- External Traffic (%)

Information Assurance
- Cross-Domain Transfer Time (sec)
- Validation Time (min)
- Authorization Management Time (min)
- Pedigree production rate (%)
- DAR compromise time (days)
- Compliant COMSEC Tier
- Incident Detection Time (min)
- Incident Response Time (min)

Enterprise Services
- Amt. Assured Data Storage (GB)
- Service Discovery Requests (Req/Hr)
- Chat Requests (Req/Hr)
- Auth. Serv (Req/Hr)
- Email (Req/Hr)
- Search (Req/Hr)
- File Dlvry (Req/Hr)
- DNS (Req/Hr)
- Service Discovery Response Time (sec)

Network Management
- Interoperability Depth - Network Tier #
- Response Time (sec)
- Time to Refresh contextual SA (sec)
- Priority Information Delivery Mgt (%)
- Connection Resilience (%)
- End User Device RF Spectrum Eff (bps/Hz)
- RF Spectrum Reallocation Time (sec)

Figure 7. QCDI Metrics by Net-Centric Capability Area

Figure 7 shows metrics chosen for the Joint network. A group of subject matter experts selected the metrics using the above criteria.

Having determined appropriate metrics, a framework for determining appropriate values these metrics is needed. For metric values to be generally applicable to DoD needs, the following conditions should be met:

- Estimated demand should be consistent with user expectations. Military users will demand what others have, particularly civilians or adversaries who also have access to commercial technology. Newer users will also be expecting the level of IT capability that they have been accustomed to receiving before entering the military.

Demand values should not be dependent on knowing exactly how systems are supposed to be used. Users will find new ways to leverage network capabilities as the demands of the situation change. Indeed, since it enhances force agility, the ability of the network to enable a wide range of TTPs or business processes, especially those unanticipated, is arguably its most important attribute.

- Demand estimates should be mitigated by what is feasible. Capabilities to satisfy demand should be potentially available in the time frame of interest. Some Architectural assumptions are made to capture the evolution of key aspects of the Joint network; e.g. the lowest echelon to which the Joint network reaches will vary over time. However, these should be kept to a minimum.

DEVICE BASED APPROACH

In order meet the need for a user oriented, widely applicable and easy to employ metrics framework, an approach based on the devices users interface with to access the network was chosen. This device based approach has been employed by others such as the Nemertes study group to assess bandwidth demand growth in the Internet.[15]

There are several reasons why this approach has advantages over other methods. First, network access devices are increasingly integrated into the daily lives of military and non-military users. Cell phones and smart phones are good examples of such devices that have become ubiquitous. Second, because commercial industry increasingly leads in the development of networking devices, military users increasingly rely on commercial products, such as laptop computers or handheld personal digital assistants. Defense contractors have grown adept at adapting commercial technologies to military needs and incorporating these technologies in military end-user devices. Therefore a device based approach can accommodate a wide range of DoD user demands, since these devices are increasingly based on the same underlying commercial technologies. Third, military users especially at the lower echelons have become increasingly accustomed to commercial devices used for accessing the Internet. In contrast, new military users increasingly will not be familiar with, easy to train, or effective with networking devices that employ arcane or unusual proprietary user interfaces—common in legacy military systems. We find evidence of this in that more DoD C2 systems are incorporating COTS applications or user interface characteristics.[16]

The above trends imply the needs of military users can be expressed in terms of common device characteristics, and that these needs can be more clearly articulated in these terms rather than in others such as the number of network nodes, architectures, network standards etc. Military users use the network in ways that are enabled by the devices they use to access the Joint network and are constrained by the limitations of these same devices. Military users are increasingly predisposed to use the Joint network as they would use commercial networks in other aspects of their lives. This is especially true in the unconventional or irregular warfare operations.

Because networked devices tend to evolve at predictable rates based on the underlying improvements to both device technologies and network infrastructure, meaningful projections of future demand based on observable growth rates is possible. This last point is especially important because while there remains deep uncertainty as to the nature of future conflicts US forces may confront, we can predict with more certainty the general characteristics of the devices that US military will use in future conflicts.

Some efforts have been made to establish an estimation framework based on the applications that users may employ rather than devices. Although this approach might provide more granularity with respect to specific users' needs, it is limited by the difficulty in predicting how applications will evolve in the future. If only a limited number of applications were available (as was once the case), this approach may be more tenable, but the "app-store" model of the commercial sector is likely to increasingly be demanded by military users and drive rapid increase in the number and diversity of applications. Simply, the application layer of the Joint network has a much higher degree of uncertainty than the device layer. It would be much more difficult to develop a predictive model of user demand by focusing on the application layer.[17]

With a device based approach there are a few key parameters that can be used to characterize the demand generated by users of a the device. The most obvious is the maximum data rate of the device. Another important factor is user duty cycle (the fraction of a given period of time that a user actively uses a device). Not all DoD users for military units employ their Joint network access devices the same way. Some, such as unit commanders, may be "heavy" users of their devices and so may have a higher duty cycle than other members of a unit. Also it is not necessary that all users of the network have a device that can access the Joint network. Certain users may simply not require access, and technical feasibility may prevent others from using certain devices types in certain timeframes, scenarios, etc. As a result, in a device-based approach the number (or density) of Joint network access devices relative to the number of users in a unit is important. Since size, weight, power, sensor resolution and other physical characteristics of unmanned systems are relatively well-known and predictable; the device based approach described here can be easily applied to unmanned systems.

By focusing on devices and the concrete, predictable characteristics of these devices, it is possible to develop quantitative estimates of demand that can be aggregated up over large military units and indeed up to and including the entire DoD enterprise.

Types of User Devices

In both the commercial and military network environments, users interact with the network through an ever growing array of devices of various types. For analysis, these devices can be grouped into a limited number of categories based largely upon how the device connects to the network and how the device is typically employed. The ubiquitous cell phone is an example of a common device type: a direct Line Of Sight (LOS) wireless device. Although cell phones are used in the military environment, a wide range of military specific LOS devices are also used such as man-portable tactical radios. Users expect direct LOS devices to provide moderate levels of network performance while in range of fixed local network infrastructure (e.g. cell tower).

When not in range of local infrastructure, direct Beyond Line Of Sight (BLOS) devices are needed. These devices typically use satellites for communications, but other options may be available (such as aerial relay) in the future. These devices are typically used outside of areas of direct LOS device coverage. Users trade relative lower performance on these devices for the flexibility of employment.

DEVICE TYPE	DESCRIPTION
Direct BLOS –	User demand directly supported through a BLOS wireless device (generally direct use of a low data rate SATCOM terminal).
Direct LOS –	User demand directly supported through use of line-of-sight (LOS) wireless device.
Indirect –	User demand not directly supported by a wireless receiver or transmission device. This demand is aggregated with demand from other users before transport outside of local area networks.

Figure 8. QCDI Device Categories

For both direct LOS and direct BLOS devices, direct connections to networks with global access is normally assumed. Devices which only provide local connectivity are generally not considered in Joint network analysis.

The third category of devices includes a broad assortment of equipment with which users *indirectly* connect to the global network. This category has two general classes. The first class contains devices producing traffic which is aggregated through a switch, router, or similar infrastructure component before connecting to external (Joint) networks. This category includes desktop computers, phones, etc. Some of the traffic from these devices remains on local sub-nets and thus is not a part of the Joint network demand. A second class of device in the indirect demand category contains devices which are normally disconnected from the Joint network, but which periodically are "synchronized" with some Joint network based resource. This synchronization may involve a number of mechanisms including manual transfer of data via CD ROM or periodic attachment to a network connected device via some sort of cable, local RF signal, etc. Figure 8 summarizes these device categories.

AGGREGATION METHODOLOGY

The previous sections have described the QCDI frameworks for users and for demand metrics, as well as the means by which estimates for the demand of individual users of different types were made. To be useful for program and portfolio analysis, however, a means by which to estimate the demand of collections of individuals (military units and other types of DoD organizations) is needed.

The QCDI accomplishes this by representing groups of users, based on real organizations, as being made of up appropriate mixes of users from the QCDI user classes in appropriate domains, echelons and eras (including non-human users such as unmanned systems and sensors). This unit characterization was done by examining the Tables of Organization and Equipment for each included unit, and parsing the billets associated with each unit into the QCDI User Classes to which they correspond, based on role, location, echelon and other considerations. While the human organization of most units was assumed to be static over the timeframes considered in the QCDI, the model does recognize the rapid growth in the use of unmanned systems. Growth factors were applied to those user classes, so that the quantity of unmanned systems increases geometrically over time.

In some cases, in particular with aircraft and unmanned systems, it is necessary to recognize that, due to logistic and other operational considerations, not all of the platforms associated with a unit will be actively involved in a mission at a given time. In these cases, the QCDI defines a mission rate for those user classes, to specify the portion of the unit's assets of that class that are active in the mission. This provides a means to deal with issues associated with operational tempo, and avoids demand estimates that assume that all platforms are operational at all times – without requiring other factors such as Duty Cycle to take on overly complex and multi-faceted meanings in different parts of the model.

The QCDI Model currently characterizes 360 military organizations across echelons and from all Services, including:

- U.S. Air Force: Composite Fighter Wings, ISR Wings, Composite Mobility Wings, C2 and intelligence aircraft, fighters (e.g., F-22, F-35, A-10), bombers and other squadrons.
- U.S. Army: All types of Brigade Combat Teams, Maneuver Enhancement Brigades, Military Intelligence Battalions, Sustainment Brigades, Other support units and various headquarters.
- U.S. Marine Corps: Full Marine Expeditionary Brigade, Marine Expeditionary Force Headquarters Group, other support, aviation and headquarters units.
- U.S. Navy: Carriers, Cruisers, destroyers, and other ships and various aviation units.

Using this information, the model computes estimates for an extremely wide range of individuals units to address Service-level analytic needs. More importantly, however, the QCDI is able to use individual unit information as building blocks, allowing QCDI users to construct and estimate the demand of multi-unit and multi-Service organizations (e.g., Joint Task Force) made up of any combination of units in the extensive QCDI database. Thus, the QCDI can be applied to address Joint and even DoD Enterprise-level issues.

Calculation of the demand estimate for a given unit is made by aggregating the demand of the individuals making up the unit, using user-level demand information. Note that different aggregation algorithms are used for different metrics, as appropriate for the nature of the demand being estimated. Metrics that characterize capacity or flow, such as data-rate-related metrics and enterprise service requests, aggregate by summing over the demand of individual users, taking into account how individual users may share devices (*sharing factor*) and the fraction of the time the users' devices are active on the network (*duty cycle*). For example, the aggregation for a metric such as Data Rate can be characterized as follows:

$$\mathrm{DR}_{unit} = \left(\sum_i \mathrm{DR}_i\right)\left(1 + ES + NM\right)\left(1 + IA\right)$$

a sum over the Data Rate demands (DR_i) of all individuals i in the unit. ES, NM, and IA represent the infrastructure overhead burdens for Enterprise Services, Network Management and Information Assurance, respectively, applied to the aggregate demand.

The Data Rate demand of an individual (for a particular device class) is the product of the data rate of the device, the sharing factor for the individual, and the duty cycle for the individual:

$$\mathrm{DR}_i = \left(\mathrm{DDR}_i\right)\left(SF_i\right)\left(DC_i\right)\left(1 + ADF_i\right),$$

where DDR_i is the *device* Data Rate for i's demand device of the type being assessed. SF_i and DC_i are i's Sharing Factor and Duty Cycle. In the basic QCDI model, the Device

Data Rate (as well as all other metrics) is considered to be the same for all users in a user class, as are the Sharing Factors and Duty Cycles. Thus, in the base aggregation, the Data Rate demand of a unit can be reduced to a sum over the user classes represented in the unit as follows:

$$\mathrm{DR}_{unit} = \left(\sum_{j} \sum_{i \text{ in } j} DR_i \right) OH$$

$$= \left(\sum_{j} \mathrm{N}_j \left(DDR_j\right)\left(SF_j\right)\left(\mathrm{DC}_j\right)\left(1 + ADF_j\right) \right) OH$$

$$OH = \left(1 + ES + NM\right)\left(1 + IA\right)$$

in which N_j is the number of users in user class j in the unit, and DDR_j, SF_j and DC_j are the Device Data Rate, Sharing Factor and Duty Cycle for User Class, j.

Other metrics having to do with network quality or reliability use MAXIMUM or MINIMUM aggregation functions where the output is determined as the value of the network's most demanding class of users. In still other cases in which it appropriate to represent the aggregate demand as the typical level or quality of some capability needed (as is the case in many information assurance metrics), the statistical mean is used to compute the aggregate demand of the unit.

A TOOL FOR THE QCDI MODEL

An Excel-based tool was created to access, present and analyze data from the QCDI model. As illustrated in the screen capture shown in Figure 9, the tool allows the user the option to view raw data in the QCDI model as well as aggregations of the data. It also allows the user to see how variations in the input data affect the aggregate outputs via built-in Monte Carlo sensitivity analysis capability.

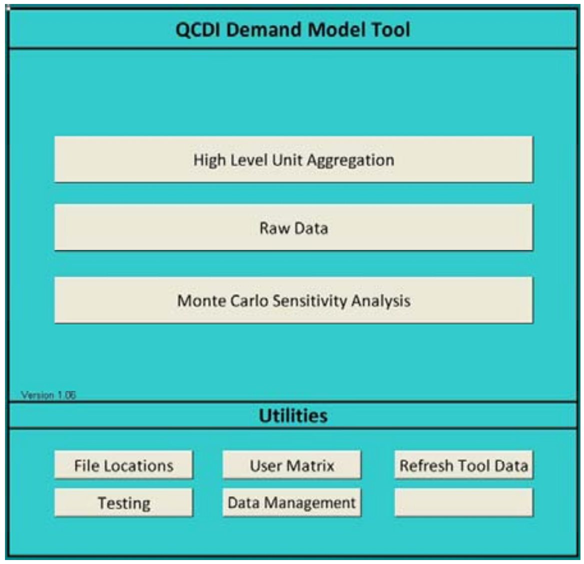

Figure 9. Screenshot of Options in the QCDI Tool

A version was released in early 2009 as a stand-alone application with an easy to use graphical interface that allows different display options. One is shown in Figure 10. The tool allows stochastic analysis. The aggregation methodology described in the previous section generates QCDI estimates of the expected demand of a unit comprised of users of different user classes, as characterized from unit TO&E and using user class values from the QCDI model. The tool presents the calculated estimates and allows analysts to change the parameters of the calculations. This allows the analyst to represent demand more richly, for a number of purposes, including:

- Conducting sensitivity analysis around QCDI demand estimates;
- Exploring the effects of alternate assumptions of user-level demand on unit demand estimates;
- Characterizing the uncertainty associated with a unit demand estimate, given uncertainty in user-level demand.

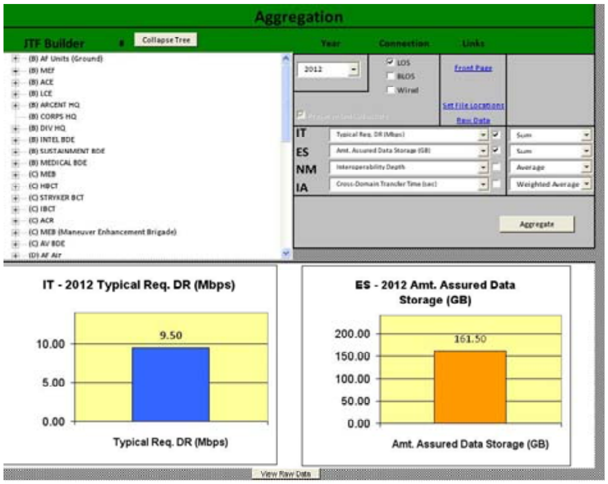

Figure 10. Notional Demand Estimates Using the QCDI Tool

Additional sensitivity analysis is provided through a range of Monte Carlo simulation options that allow for demand estimation that includes stochastic considerations at different levels. Users of the tool can select or define distributions for the values of all metrics at either the user class or individual user levels and see the distribution of aggregate demand estimates that result from their selections. At the user

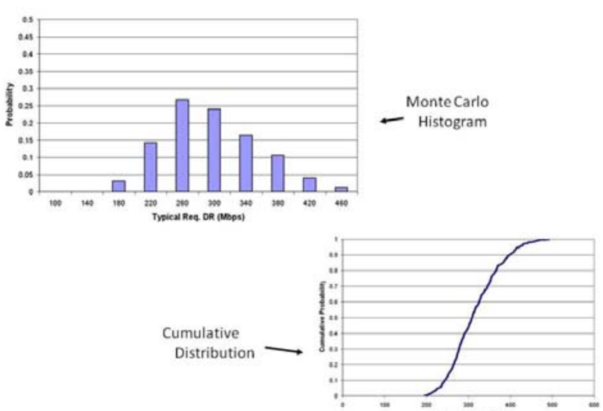

Figure 11. Sample QCDI Output Using Stochastic Tools

class level, this is invoked by drawing a value for the entire user class and then aggregating. It is useful for dealing with what-if questions regarding broad classes of users.

If Monte Carlo draws are done at the user level, however, the QCDI tool treats each user independently, drawing the value for that individual for the metric of interest (as well as sharing factor and duty cycle, as desired) from the distribution specified for the user class to which that individual belongs. Different distributions can be specified for each metric and each user class. In this mode, rather than employing the simple multiplicative equation described in the previous section, the demand for each individual is selected and aggregated according to the method appropriate for each metric. Figure 11 shows the type of output available with stochastic analysis feature of the QCDI tools.

APPLICATION APPLYING THE QCDI TO REAL ANALYSIS PROBLEMS

In 2009, approximately 20 formally chartered efforts used the QCDI model as a basis for joint network demand. This level of usage in the first year of availability demonstrates the need for a model like the QCDI as well as the utility of the model for real analysis needs. Examples of application of the model can be found in all three physical warfighting domains: Ground, Air, and Maritime. In the Ground Domain, the model was used for numerous efforts including estimation of data rate requirements for combat brigades in the 2012-2020 timeframe. Results produced by the model for a range of combat brigade types fell into the mid range of results from other modeling efforts across a range of scenarios. In the Air Domain, the model has been used to quickly estimate the demand for the next generation of data links. Results in this case were obtained in hours and closely aligned with results from a several month long IER based study. In the Maritime Domain, the model has been used to determine the minimum level of network performance necessary in a contested cyber environment, again producing similar results to a near simultaneous, but much more resource intensive study effort.

CONCLUSION

The exponential growth in bandwidth demand observed in the Internet and DOD networks exemplifies the need for better and more accurate methods for predicting joint network capability needs. The QCDI demand model was developed to address this need and to better represent the wide range of capabilities the joint network provides to a diverse set of users across the DoD. The QCDI model balances the need for representing the many capabilities of the joint network in a tractable manner by using a relatively small number of metrics and allowing control of critical dimensions of demand. It represents the Information Transport (IT), Information Assurance (IA), Metwork Management (NM), and Enterprise Service (ES) aspects of the joint network. It includes discrete representations of several hundred different military units and bases. The QCDI web-based tool enables analysts to aggregate demand for an arbitrary collection of these units to quickly obtain estimates for the spectrum of demands these units would present to the joint network in a real military operation. The utility and flexibility of this device based demand model has been demonstrated by its quick adoption in numerous DoD and Service level analysis efforts.

Work is now underway to extend the QCDI demand model to explicitly reflect the possibility of a heterogeneous device distribution within a unit and temporal demand effects due to dynamic demand changes and the concurrent use of network resources. In the near term, the QCDI model will be augmented to treat sharing factor and duty cycle as probabilities rather than fractions. The longer term vision is to model users as interdependent demand generators. In 2010 the model is available online for approved users. A screen shot of a version of web tool is shown in Figure 12. This is expected to increase the use of model and provide valuable feedback to support its expansion and refinement.

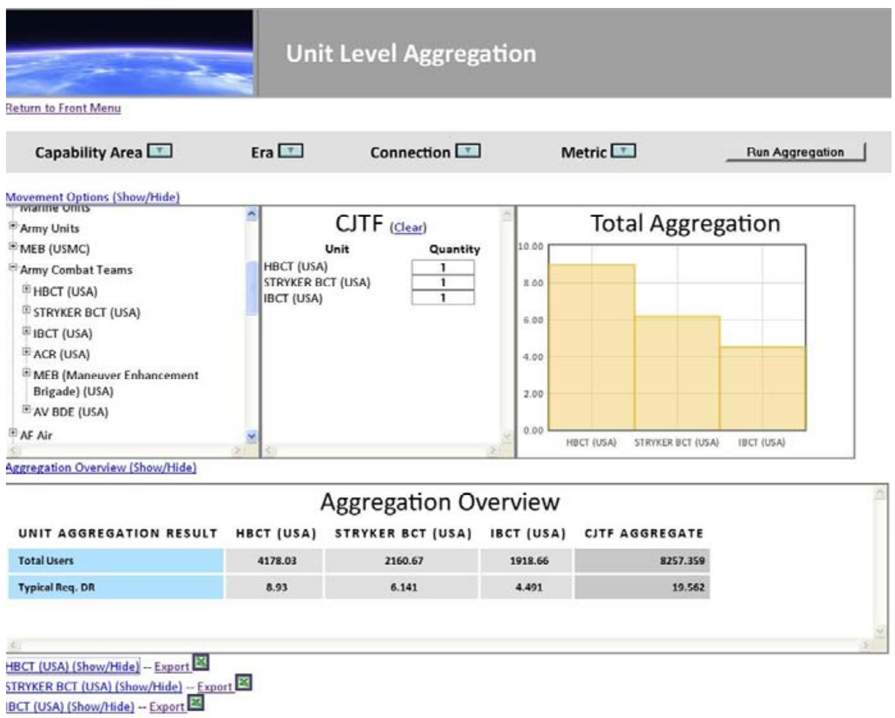

Figure 12. Sample output of web-based QCDI Model

Those interested in using the model or obtaining more information about the QCDI should contact Craig Burris at craig.burris@jhuapl.edu or Dan Gonzales at gonzales@rand.org.

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